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A PRELIMINARY STUDY OF THE STRATOSPHERIC WARMING OF DECEMBER 1967–JANUARY 1968

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ABSTRACT

The major stratospheric warming of December 1967–January 1968, which reached its peak nearly 1 mo earlier in the winter than any other major warming of record, is compared with other stratospheric warming events, especially with that of January 1963, through the use of rawinsonde and rocketsonde information. This information is presented in the form of time sections, spatial cross-sections, and constant-pressure synoptic charts at various stratospheric levels for representative dates before the warming and at various stages of its development. Synoptic density charts at 30 and 40 km are presented showing marked changes in stratospheric densities during the warming from both standard atmosphere and nonwarming conditions. Spherical harmonic analyses of height fields are used to show the importance of components of zonal wave number 2 in changes of stratospheric circulation associated with the warming.

1. INTRODUCTION

Even though an extensive literature dealing with sudden stratospheric warmings is already in existence, we still have an incomplete understanding of causes, processes of development, and relationships between circulation and thermal patterns at different stratospheric levels during these events. Moreover, the intriguing problem of coupling between the stratosphere and the mesosphere and between the stratosphere and the troposphere is still a challenge.

Our lack of knowledge is in part due to the relatively infrequent occurrence of large-scale midwinter warmings as well as the relatively small amount of data available at middle and upper stratospheric levels during warming periods. Major studies have so far been largely confined to the warmings of 1952, 1957, 1958, and 1963, but some evidence concerning earlier Arctic warming episodes has been collected (Wilson and Godson, 1963). Midwinter Antarctic warmings have been discussed by several writers, although the scarcity of Southern Hemisphere data has permitted controversy on the extent of the phenomenon in the Antarctic (Belmont et al., 1968; Julian, 1968).

Besides providing an additional opportunity for testing theories of stratospheric warming development, the Northern Hemisphere warming of December 1967–January 1968 was of special interest for at least two additional reasons: 1) the time of the initial observation of the warming at the 10-mb level (around December 17) was nearly a month earlier than that of any other major stratospheric warming previously catalogued, and 2) preceding the warming, westerlies of near-record intensity were observed in the upper stratosphere over western Europe. The West Geirinish (57°21′ N., 7°22′ W.) rocket sounding for December 13 showed a wind speed of over 175 m sec^{-1} at the 47-km level (fig. 1). This speed is claimed to be a record maximum for the free atmosphere (Anonymous, 1968).

2. SYNOPTIC DEVELOPMENT OF THE WARMING

CONDITIONS PRIOR TO THE WARMING

During November and early December 1967, the usual winter cold cyclonic vortex dominated the polar stratospheric circulation above 100 mb in the Northern Hemisphere. At 10 mb the vortex deepened more rapidly than in any of the three preceding winters, attaining a minimum central height of 2800 geopotential decameters on Dec. 13, 1967.

Associated with the unusually rapid deepening of the vortex was a sharp increase in the mean zonal geostrophic wind. Along 60° N. latitude, the mean speed at 10 mb reached nearly 60 m sec^{-1} during the period of December 9–14. This is more than 25 percent greater than speeds for this period during any of the years 1964–66. The previously mentioned maximum observed wind at West Geirinish (fig. 1) occurred at this time; although due to a lack of data, no relationship between this 47-km wind maximum and the strengthening of 10-mb winds can be demonstrated.

INITIAL STAGES OF THE WARMING (DEC. 15–27, 1967)

The first sign of warming was observed at West Geirinish in the 45–50-km region on December 13 (fig. 1). The sparsity of data does not permit any conclusion about the direction of propagation of the warming event, but further evidence of its early progress is given by the 4.0°C temperature observed over Berlin, Germany, at 38 km on December 19 (fig. 2). This marks the maximum observed effect of the warming at Berlin, being more than 40°C above the Committee on Space Research International Reference Atmosphere (CIRA) standard atmosphere value.

At the 10-mb level, the warming was first seen with the development of a warm ridge in the vicinity of the

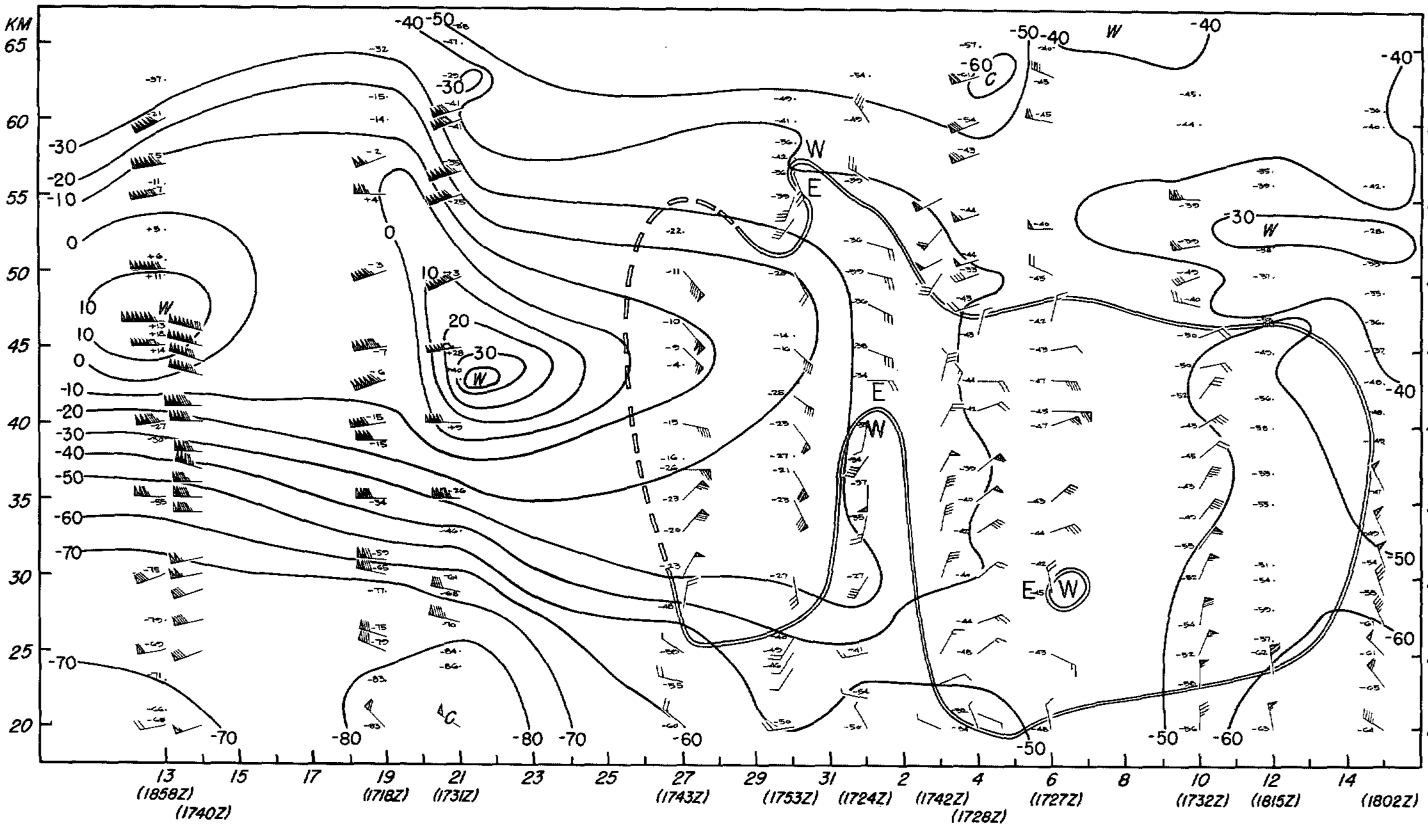

FIGURE 1.—Time section of West Geirinish, England, rocket soundings for Dec. 13, 1967–Jan. 14, 1968 (GMT). Temperatures are in degrees Celsius, and winds are in knots with full barbs for each 10 kt and flags for each 50 kt. The double line separates easterly winds, indicated by (E), from westerly winds, indicated by (W). Italic (*C*) and (*W*) indicate cold and warm centers, respectively.

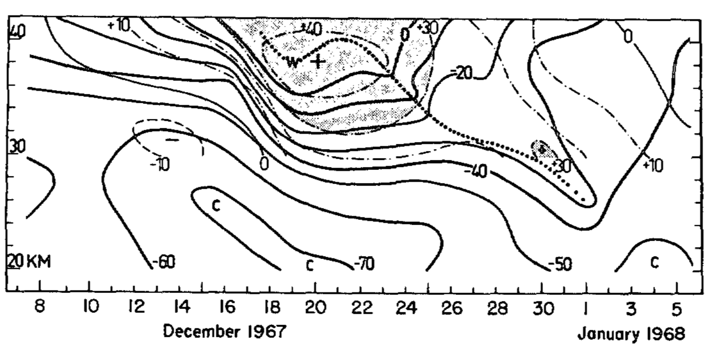

FIGURE 2.—Time section of temperature for Berlin, Germany, Dec. 7, 1967–Jan. 6, 1968 (adapted from Labitzke and Schwentek, 1968). Isotherms are solid lines labeled in degrees Celsius and stratopause heights are shown by heavy dotted lines. Deviations from the Committee on Space Research International Reference Atmosphere (CIRA) 1965 standard atmosphere are plotted as thin broken lines labeled in degrees Celsius with deviations over +30°C shaded.

Azores about December 15. The movement of the warm air center (temperature above −30°C) was eastward in the following days, reaching the central Mediterranean area by December 21. The center then moved northward and was located over Berlin on December 25 (fig. 3).

Although abnormally warm air was not observed at levels much below 10 mb, ridge development was noticeable over the North Atlantic Ocean and western Europe by December 25. The extent of the circulation change on this date is comparable to that of Jan. 18, 1963 (cf. fig. 3 with fig. 2 of Finger and Teweles, 1964). Meanwhile, easterly winds over the southeastern United States delineated an east-west ridge line moving north from the Carribbean. This ridge line was centered in the vicinity of 32° N. on December 25.

Rapid northwestward movement of the warm center occurred at the 10-mb level during succeeding days, with an average rate of movement of 15° of latitude per day. Temperature changes were even greater at higher levels, as seen on the 2- and 0.4-mb charts for December 27 (figs. 4A, B). These show circulation patterns similar to those found on January 27 during the 1963 warming (Finger and Teweles, 1964). The division of the polar vortex into two parts, seen most clearly at 0.4 mb, preceded the development of a similar bipolar circulation at 10 mb.

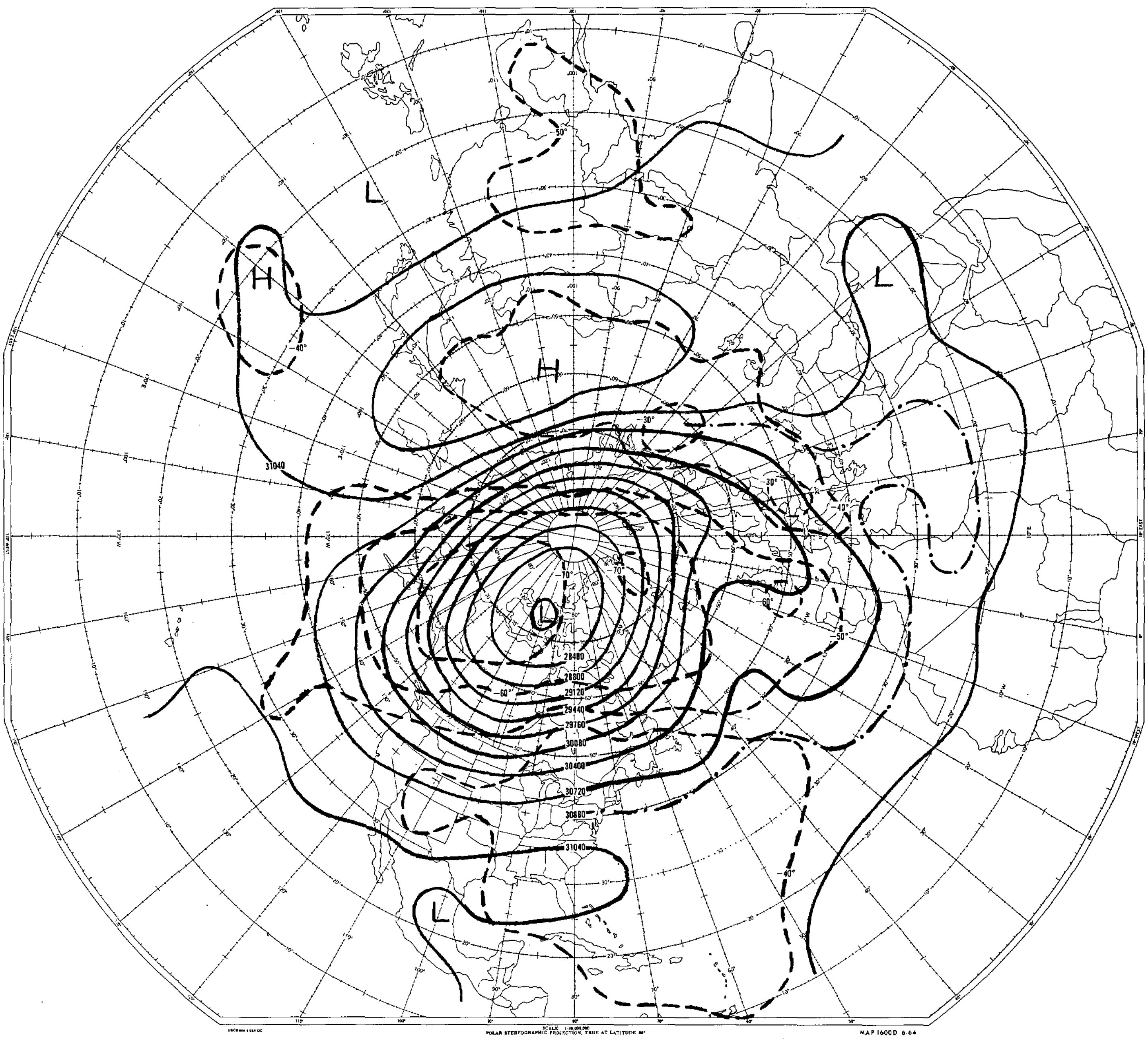

FIGURE 3.—The 10-mb chart for 1200 GMT, Dec. 25, 1967. Contours are solid lines at intervals of 320 m, with an intermediate contour introduced as a dash-dot line. Isotherms are dashed lines at intervals of 10°C.

At much higher levels, ionospheric soundings by wave-interaction techniques carried out at The Pennsylvania State University (Rowe et al., 1968) indicated a tenfold increase in electron density at the 75–80-km level during this period. Maximum electron densities were observed on December 30. The explanation advanced for this event was an increase in nitric oxide (NO) concentration for which the most probable explanation is in situ warming. However, other explanations of the increased electron density are possible. It should also be noted that there was no observation of abnormal electron densities below 70 km (Mitra, 1968).

Changes in mean zonal temperatures associated with the warming at 10 mb can be seen in figure 5. The poleward movement of the high temperatures beginning at low latitudes on December 15 and reaching higher latitudes during the next few days indicates that even though the warming initially took place over less than half of the hemisphere, its effects were so pronounced as to result in substantial increases in the mean zonal temperatures

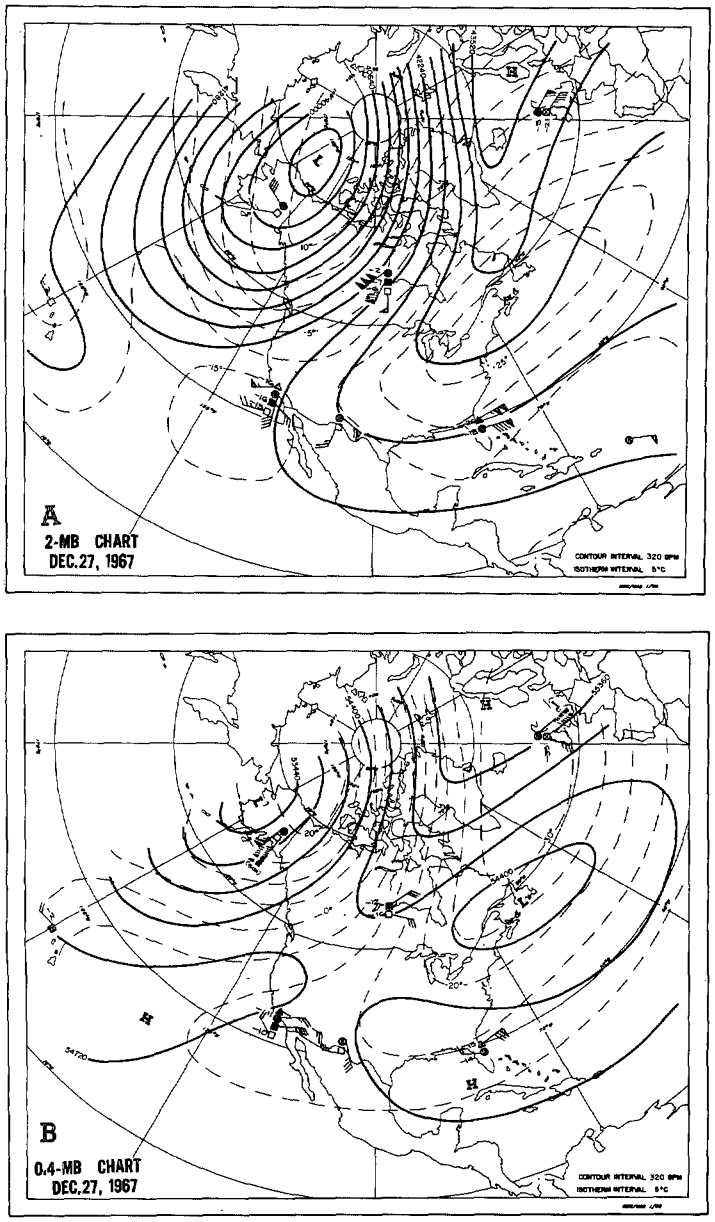

FIGURE 4.—(A) 2-mb chart and (B) 0.4-mb chart for Dec. 27, 1967. Plotted rocketsonde winds in knots with full barbs for each 10 kt and flags for each 50 kt. Temperatures are in degrees Celsius. Observations are noted as follows: open triangle, more than 1 day before map date; filled triangle, the day before map date; filled circle, map date; filled square, the day after map date; open square, more than 1 day after map date.

and finally in reversal of the normal mean temperature gradient.

CIRCULATION BREAKDOWN (DEC. 27, 1967–JAN. 10, 1968)

Northward motion of the Atlantic ridge line continued with eventual division of the polar vortex into two cells and transport of warm air into the vicinity of the North Pole. (By December 27 the temperature gradient between the North Pole and midlatitudes had reversed. A similar reversal of temperature gradient occurred by January 27 during the 1963 stratospheric warming.) The time section for Eureka, Northwest Territories, 80° N., 86° W. (fig. 6), shows the development of strong southerly winds near the 10-mb level in conjunction with the rising temperatures.

The 30-mb chart for January 3 shows development of a bipolar vortex at midstratospheric levels (fig. 7). Since there is noticeable slope with height in the cyclonic and anticyclonic systems, the bipolar vortex cannot be found at higher levels with the available data, although the circulation pattern at these levels is noticeably perturbed from the typical winter circulation (fig. 8).

The bipolar circulation continued to dominate the middle stratosphere during the succeeding 2 weeks; during the days after January 3, however, the most important new feature was the downward propagation of the warming from the 10-mb level. Initially, this downward propagation can be seen on the Berlin time section (fig. 2) about January 1. The intensity and speed of development of the warming decreased with decreasing altitude. A cross section along a great circle from Salem, Oreg., to London, England, for 0000 GMT on Jan. 9, 1968 (fig. 9), shows warming at the 50-mb level and above. A temperature gradient of 30°C in about 600–700 km across north-central Canada can be noted. During unperturbed periods, the temperature gradient here would be less and in the opposite direction.

During the warming, temperature changes up to 10°C per day were observed at the 50-mb level. Although the general path of the warm center at 50 mb followed rather closely the path at 10 mb, there was an increasing time lag between maximum temperatures at the two levels as the warming moved from Europe to North America. For example, at Berlin the time lag between the 10-mb maximum temperature and the 50-mb maximum temperature was 2 to 3 days (fig. 2), while at Eureka the time lag was 7 to 8 days (fig. 6). Time sections from the 1963 warming indicated a nearly continuous downward propagation of warming, rather than the variable time lag observed in the case of 1967–68.

CIRCULATION RESTORATION (JAN. 10, 1968, AND FOLLOWING)

After the passage of the warming over a location, both horizontal and vertical temperature gradients were reduced. The stratosphere became nearly isothermal in the vertical, and the mean zonal temperature gradient was less than that prevailing before the warming (fig. 5). By the end of January, the mean temperature gradient between 17.5° and 82.5° N. latitude was only about 20°C compared with 35°C before the warming. Winter circulation patterns were gradually reestablished but did not develop the intensity noted before the warming.

3. DENSITY VARIATIONS DURING THE STRATOSPHERIC WARMING

Quiroz (1968) has discussed the preparation of synoptic density charts for 30 and 40 km. His charts for Jan. 6,

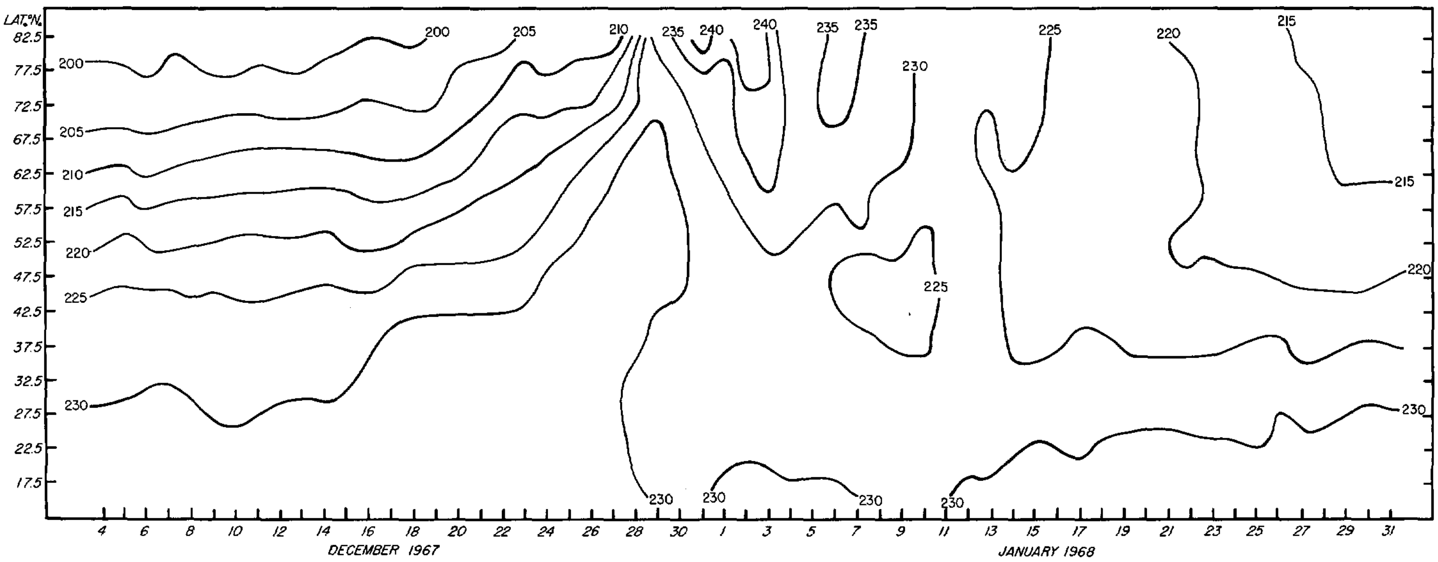

FIGURE 5.—Mean zonal temperatures at 10 mb in degrees Kelvin, 17.5°–82.5° N. latitude for December 1967–January 1968. Isotherms at 5° intervals.

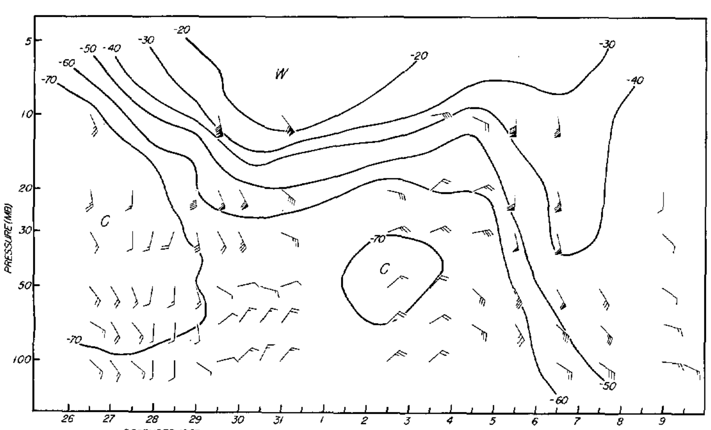

FIGURE 6.—Time section of rawinsonde observations at Eureka, Northwest Territories (80° N., 86° W.). Symbols are the same as those in figure 1, except that warm and cold centers are labeled with upper case (W) and (C), respectively.

1965, at 30 and 40 km may be regarded as typical winter charts, with low-density centers near 80° N. and between 40° W. and 80° E. on the Atlantic side of the North Pole. The density minimum is 2.4 gm m^{-3} (40 percent below the standard atmosphere value) at 40 km and 13.0 gm m^{-3} (29 percent below the standard atmosphere value) at 30 km. The high-density center is in the vicinity of the Aleutian anticyclone, and the density gradient between maximum and minimum density centers has a maximum value of 0.180 gm m^{-3}/(deg lat.) at 30 km.

Density charts for late December 1967 and January 1968 show noticeable contrasts with those for 1965. The 30-km density chart on December 27 (fig. 10) shows the shift in density patterns associated with the warming. The developing bipolar circulation and thermal fields were associated with an elongation of the polar low-density center and development of two centers of high density at 30 km. The gradient from low- to high-density centers (0.162 gm m^{-3}/(deg lat.)) was slightly stronger than on Dec. 6, 1967, although still well below that for Jan. 6, 1965.

Near the conclusion of the warming, the 30-km chart for Jan. 10, 1968 (fig. 11), shows a ridge of high density extending across the North Pole, with a secondary area of high density over the eastern United States. The maximum density gradient had about the same magnitude as on Dec. 6, 1967, but had an east-west orientation (from the Aleutians to the west coast of Canada) instead of north-south.

The 40-km chart for Jan. 10, 1968 (fig. 12), can immediately be recognized as differing considerably from other winter charts. Gradients are much weaker than on other charts. The steepest gradient between the low-density center and the high-density center is 0.015 gm m^{-3}/(deg lat.), less than one-third of the value on other winter 40-km charts. The most noticeable feature is a ridge of high density from Greenland across the North Pole to the vicinity of Sakhalin Island.

In summary, the most noticeable effects of the stratospheric warming on the density fields are: 1) displacement of the low- and high-density centers from their normal positions, and 2) decrease in and reorientation of the maximum density gradients.

Quiroz (1968) also presented an analysis of the density changes that might be encountered along the trajectory of a lifting reentry vehicle in a typical midwinter situation. It is evident that during the mature stages of a stratospheric warming, the density profiles encountered would be substantially different.

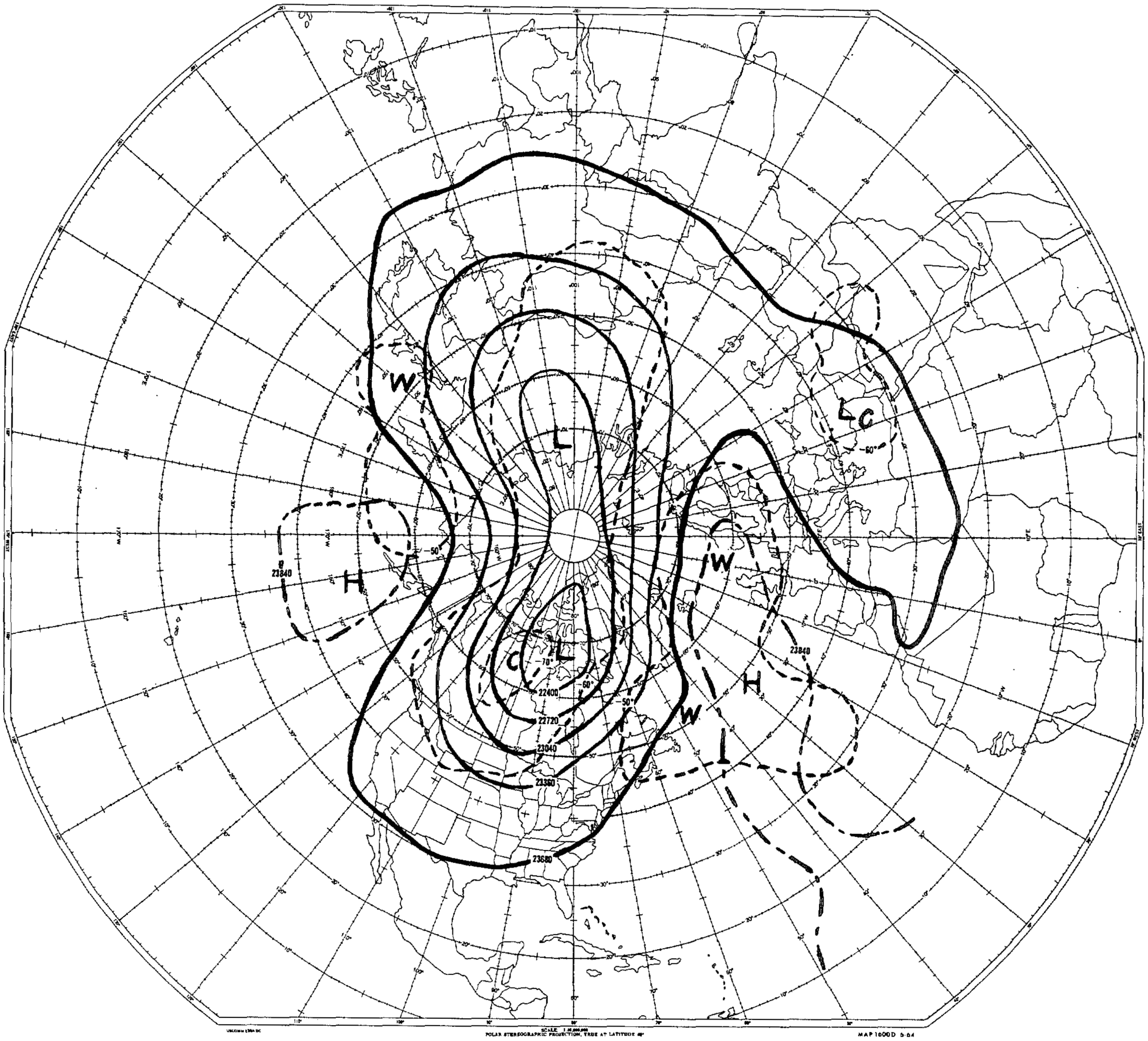

FIGURE 7.—Thirty-millibar chart for 1200 GMT, Jan. 3, 1968. Explanation is the same as that for figure 3.

4. TEMPERATURE AND HEIGHT VARIABILITIES

The effect of the stratospheric warming upon the December 1967 and January 1968 monthly means and standard deviations of daily analyzed temperature values from these means is summarized in table 1. Values for 1964–66 were presented in an earlier paper (Johnson and Gelman, 1968), in which the technique for calculating these statistical values was discussed.

In December, monthly mean temperatures were but little changed from the means for previous years. During January, however, mean temperatures were as much as 20°C higher than in January of the other years shown.

Time traces of analyzed temperature at high-latitude locations show bimodal distributions similar to those discussed by McClain (1962). A sample temperature trace for Thule, Greenland, is shown in figure 13. As in the cases discussed by McClain, it follows that at these locations the monthly mean temperatures for warming months are highly nonrepresentative of the temperatures for any particular day of the month. This bimodal temperature distribution results in an increase in the standard deviation for the month over values for months with unimodal distributions. For months with bimodal distributions, the increased standard deviations are due to the great range in values between the two temperature

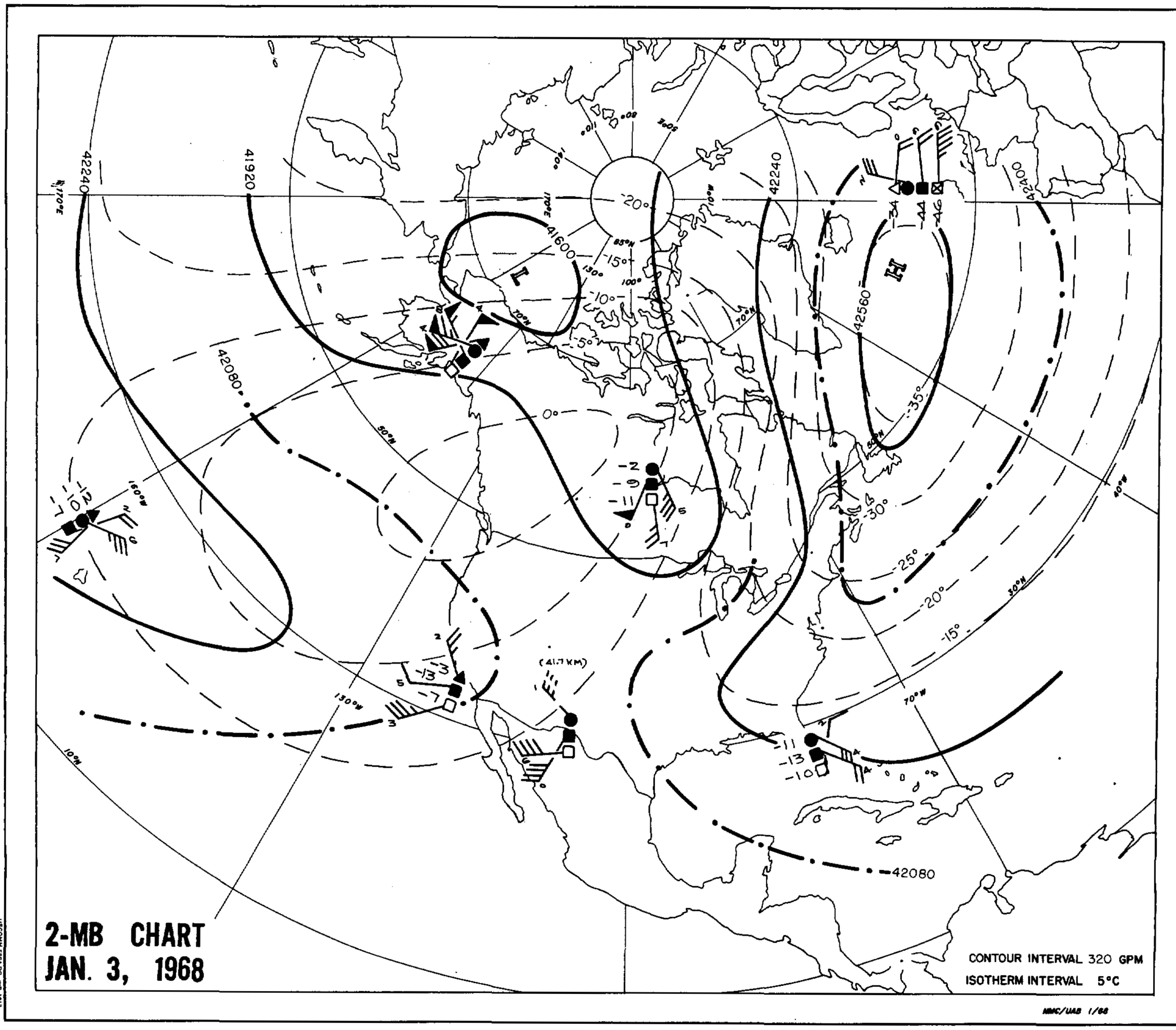

FIGURE 8.—Two-millibar chart for Jan. 3, 1968. Explanation is the same as that for figure 4.

regimes; but for months with unimodal temperature distributions, the standard deviation results principally from small day-to-day temperature changes. In studying a bimodal temperature regime, caution must therefore be exercised in reaching any conclusion based upon the assumption of quasi-normality or linear trend of the temperature trace.

Calculations of stratospheric variability during this warming thus indicate the following: 1) December monthly mean temperatures are not greatly different from those of December in other years shown, since colder temperatures before the warming compensate for higher temperatures during the warming. 2) Upon completion of warming monthly mean temperatures were as much as 20°C higher than in nonwarming years. 3) The relatively small day-to-day variation of temperature following the warming resulted in a smaller monthly standard deviation following the warming than in nonwarming winters or in months before and during the warming. 4) During December, the temperature changes at any given high-latitude location were so pronounced as to produce a standard deviation two or three times that found in December of nonwarming years.

5. SPHERICAL HARMONIC ANALYSIS

Spherical harmonic analyses of height fields over the Northern Hemisphere were performed during the warming period. Procedures for carrying out spherical harmonic

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analyses from discrete meteorological data fields are discussed in such works as those of Ellsaesser (1966) and Byron-Scott (1967). In the present study, both odd and even modes were calculated, with odd modes being discussed here in order to facilitate comparison with previous studies.

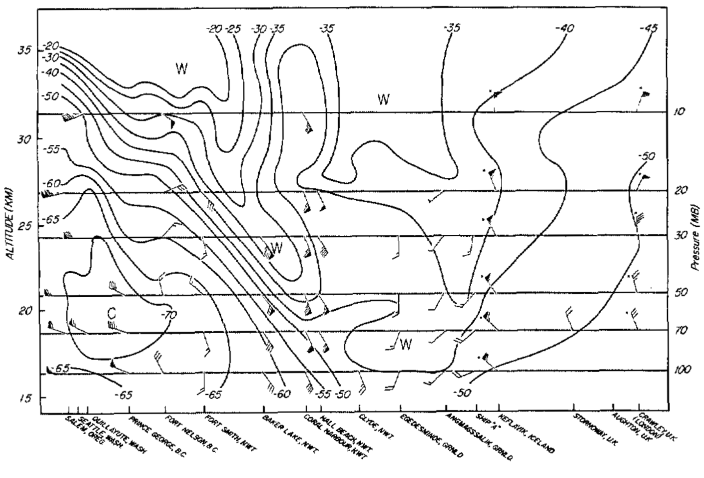

FIGURE 9.—Cross section of great-circle route from Salem, Oreg., to London, England, on Jan. 9, 1968, 0000 GMT. Off-time 1200 GMT observations are indicated by an asterisk. Observations within 200 n.mi. of the route are utilized. The symbols are the same as those in figure 1.

Deland and Johnson (1968) made use of spherical harmonic analyses of height fields at several levels. In general, coherent patterns of variations of the wave vectors from day to day could be followed for the broadest scale of waves. From these spherical harmonics, expressed in two-dimensional vector component form, vector correlation coefficients between the 500-mb level and other levels were calculated for 1-mo periods. In general, correlation coefficients for stratospheric levels were higher during winter months than summer months. Highest correlation coefficients were usually found for wave H_5^2,* which could be associated with middle- and high-latitude continent-ocean forcing (cf., Saltzman, 1965).

*In the standard notation for spherical harmonics, the superscript refers to a zonal wave number and the difference between the superscript and the subscript corresponds to the number of nodes from the North Pole to the South Pole. Thus, for example, H_5^2 corresponds to a zonal wave number 2 and meridional wave number 3, with nodal parallels at 31.5° N., the Equator, and 31.5° S. Haurwitz (1940) shows a pictorial representation of this wave surface in his figure 62.

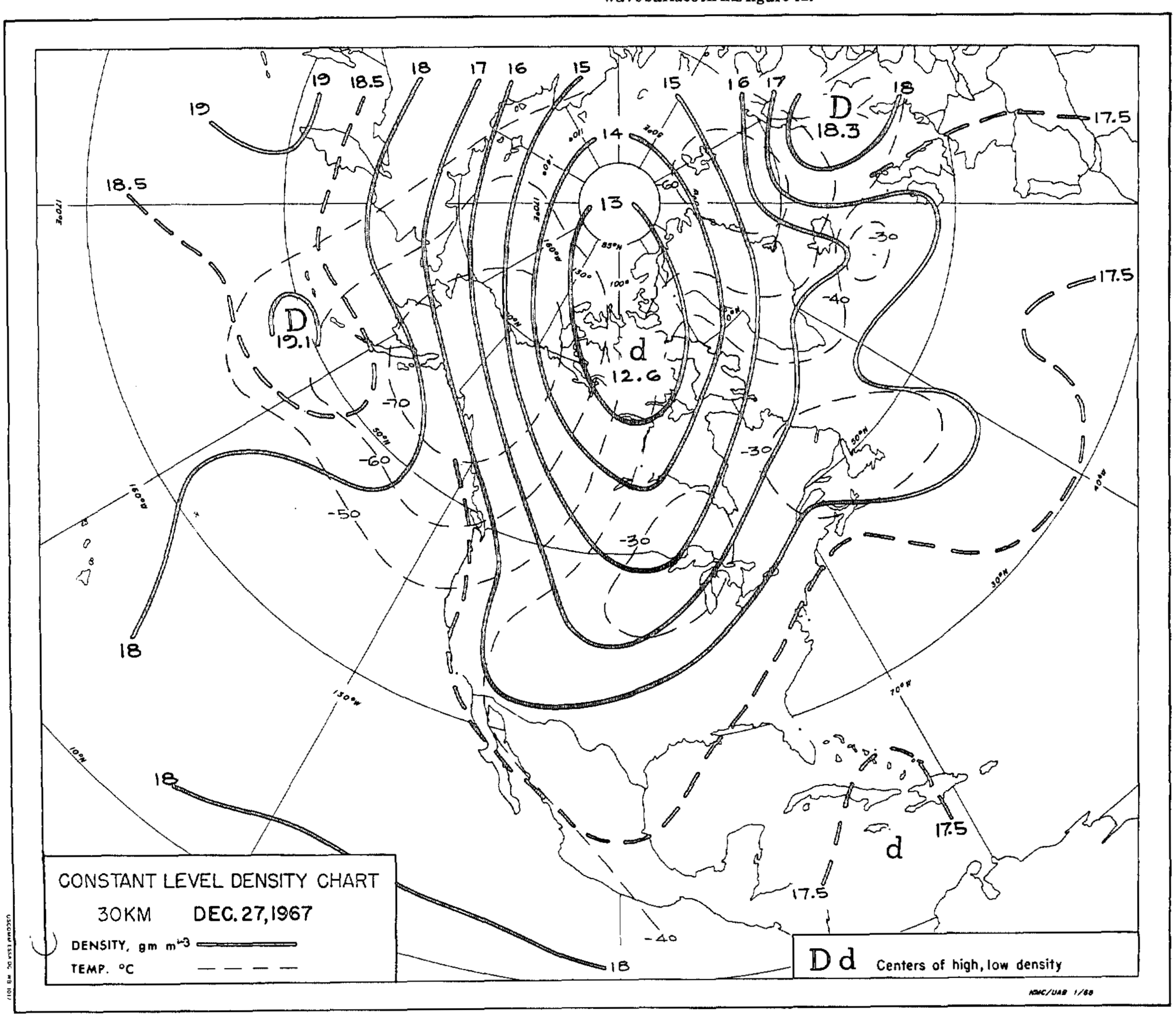

FIGURE 10.—Constant-level density map for Dec. 27, 1967, at 30 km. Heavy lines are isopycnics with a 1.0 gm m^{-3} interval. Heavy dashed lines are intermediate isopycnics introduced to aid in definition of the density field. Light dashed lines are isotherms with a 10°C interval.

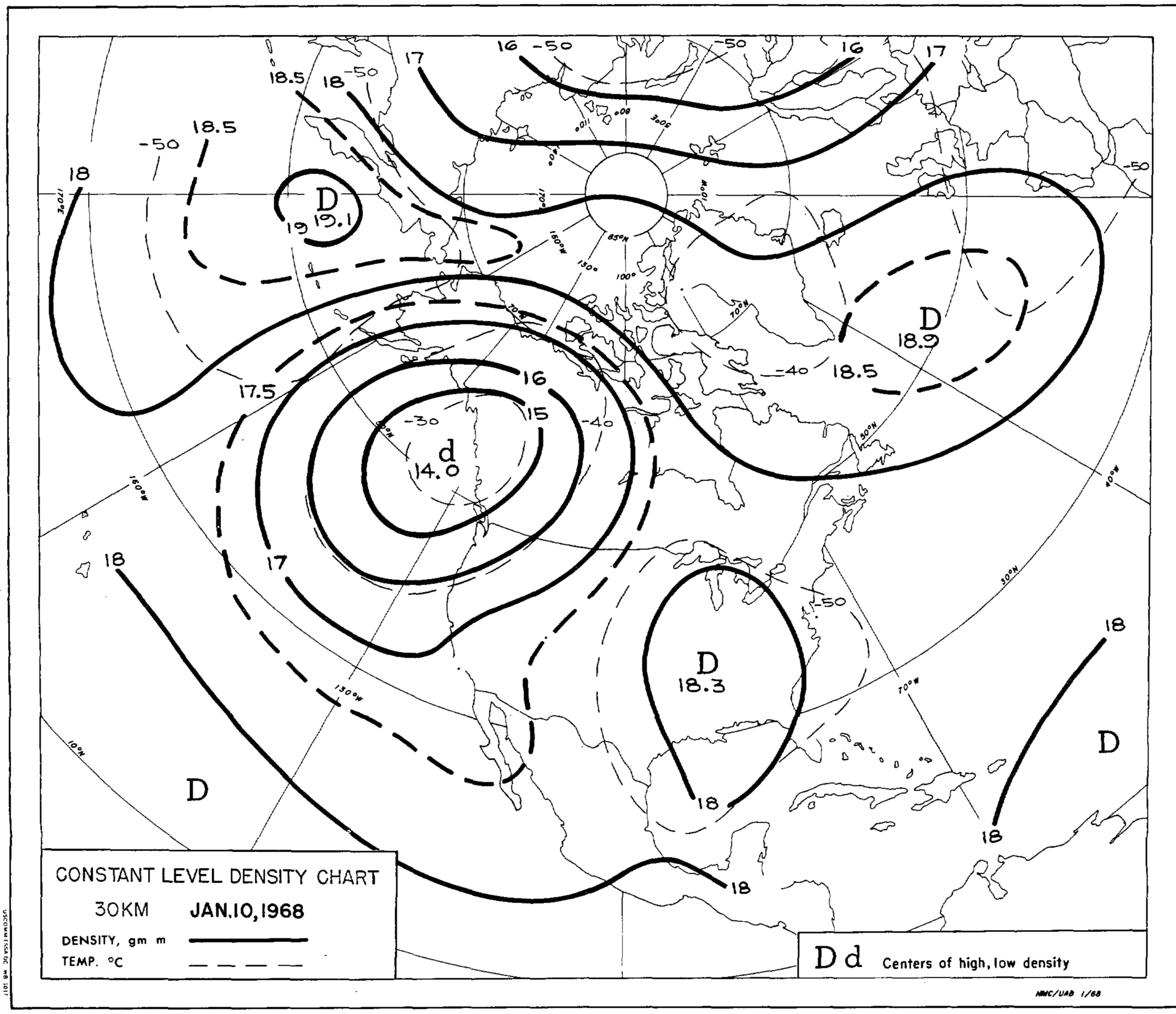

FIGURE 11.—Constant-level density map for Jan. 10, 1968, at 30 km. Explanation is the same as that for figure 10.

In the present study, the vertical correlations of 150-mb heights vs. 500-mb heights, 10-mb heights vs. 500-mb heights, and 10-mb heights vs. 150-mb heights were calculated during the warming period. In table 2, vertical correlation coefficients are compared with values calculated by the method used by Deland and Johnson (1968) and Deland (1968).

The reduction in these correlation coefficients for the warming period when compared with values for nonwarming months is immediately apparent. We would call attention to the generally higher correlations of H_{10} vs. H_{150} than of H_{150} vs. H_{500}, suggesting that the planetary-scale waves at 150 mb are more closely correlated with middle stratospheric levels than with middle tropospheric levels. Unfortunately, correlations of H_{10} vs. H_{150} for nonwarming periods have not yet been carried out.

A second procedure was used to ascertain if there were any regular phase shifts between the wave vectors at different levels. This was accomplished by recalculating vector correlation coefficients for various lags and leads of vectors at one level with respect to the other. Results for H_{10} vs. H_{150} are shown in figure 14. There is some indication of a phase shift of the order of 2 to 3 days, with the 10-mb height waves leading the 150-mb height waves. Correlations between the 10-mb and 500-mb values (for a slightly longer period) are lower in value than those for the 10-mb on 150-mb waves and are probably little above the random noise level for a vector correlation relationship.

In discussing traveling planetary-scale waves (TPSW), the traveling wave change is the change in the wave vector from 1 day to the next (Deland and Johnson, 1968). These changes are calculated for a period of 1 mo. From these values, vector autocorrelation coefficients with 1-day lags are calculated. These autocorrelation coefficients are then a measure of the regularity with which

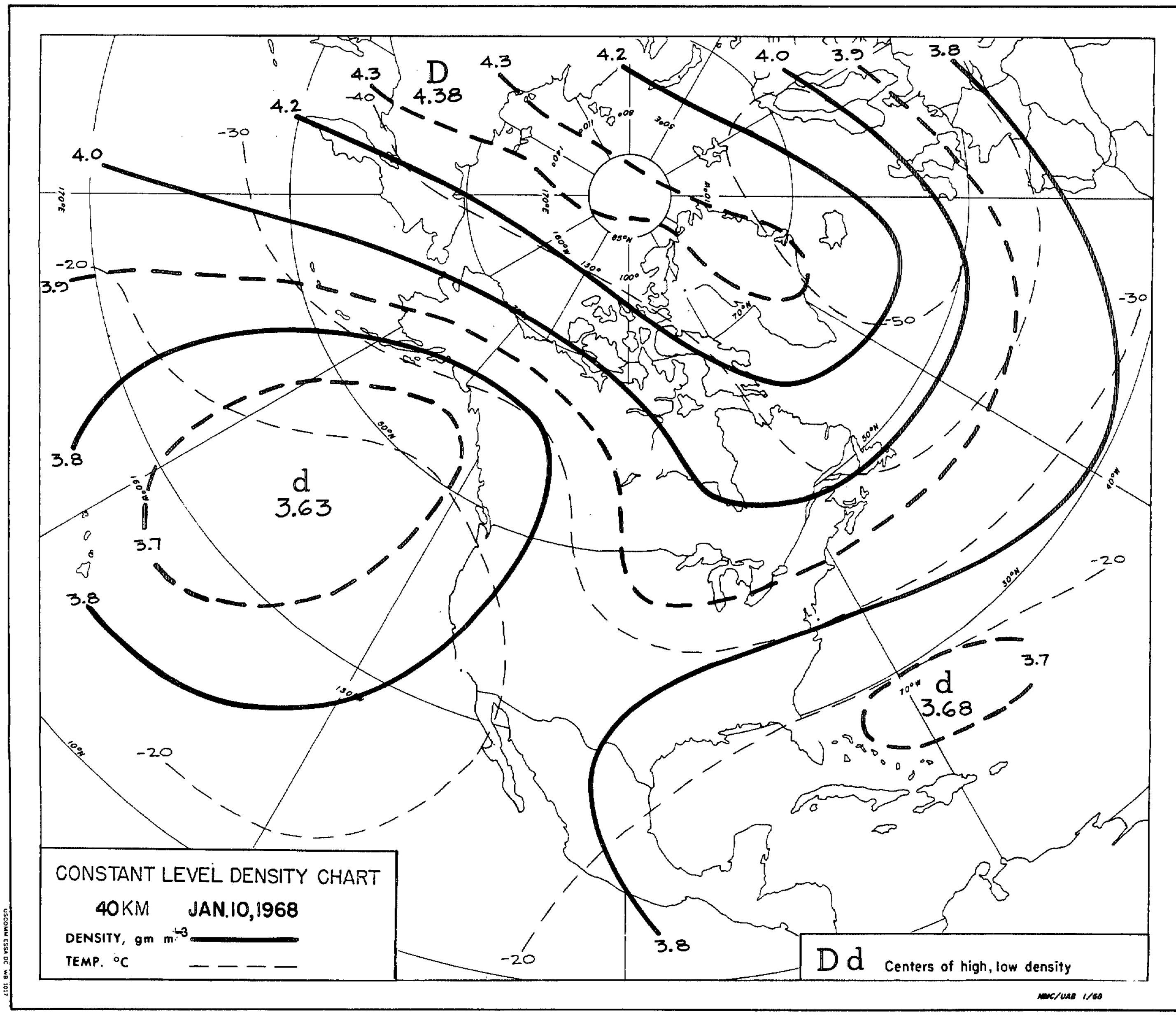

FIGURE 12.—Constant-level density map for Jan. 10, 1968, at 40 km. Basic isopycnic interval is 0.2 gm m^{-3}. Other explanation is the same as that for figure 10.

the TPSW position for 1 day can be used to predict the TPSW position for the succeeding day. Low values indicate poor predictability, due probably to interactions with other waves at the same level or to vertical interactions.

In table 3, it can be noted that at 10 mb the vector autocorrelations for the components of zonal wave number 1 for December 1967–January 1968 are above the values for November 1964 and January 1965 and are close to the values for December 1964. Values for components of zonal wave number 2, on the other hand, are noticeably smaller than those for the other months. This would suggest nonlinear or vertical interactions associated with wave number 2 components as being associated with the warming event.

At 150 mb, it is seen that most of the autocorrelation values during the warming are higher than those for November and December 1963. This would suggest that changes in the broadest and longest waves at the 150-mb level during the warming period may be explained largely in terms of simple linear, traveling planetary-scale waves.

7. CONCLUSIONS

The following conclusions have been reached concerning the warming of December 1967–January 1968:

TABLE 1.—*Monthly mean 10-mb temperatures and standard deviations at selected locations (degrees Celsius)*

	December							
	1964		1965		1966		1967	
Location	T.	S.D.	T.	S.D.	T.	S.D.	T.	S.D.
North Pole	−72	3	−60	7	−70	6	−69	13
Keflavik	−71	5	−61	7	−69	5	−63	16
Thule	−73	3	−58	6	−67	6	−68	18
Churchill	−62	5	−55	4	−62	6	−61	16
Wallops Is.	−45	6	−54	3	−51	2	−45	6
Cape Kennedy	−40	3	−48	3	−41	3	−43	3
White Sands	−44	5	−53	3	−48	3	−47	5

	January									
	1964		1965		1966		1967		1968	
Location	T.	S.D.	T.	S.D.	T.	S.D.	T.	S.D.	T.	S.D.
North Pole	−74	3	−69	5	−72	3	−73	4	−49	9
Keflavik	−75	4	−76	4	−67	5	−72	4	−45	11
Thule	−72	5	−71	3	−71	3	−74	3	−46	9
Churchill	−53	7	−58	7	−64	4	−61	7	−49	9
Wallops Is.	−48	4	−49	3	−49	4	−51	5	−49	2
Cape Kennedy	−44	2	−43	2	−41	3	−44	2	−46	3

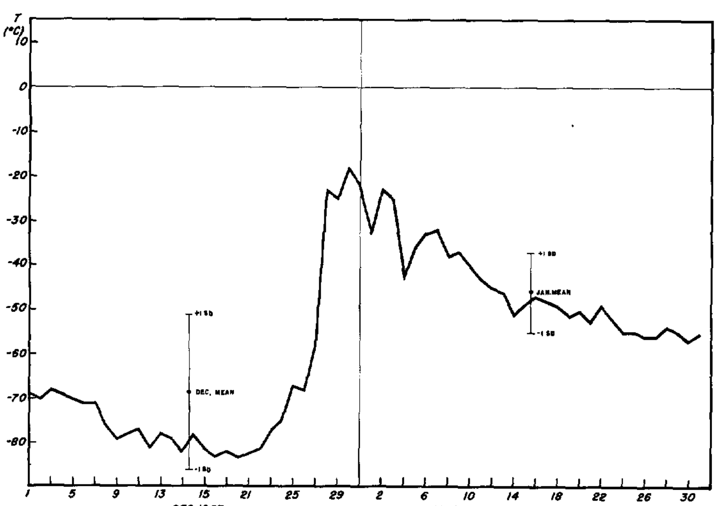

FIGURE 13.—Analyzed 10-mb temperature values (degrees Celsius) at Thule, Greenland, December 1967–January 1968. Monthly means and intervals of plus or minus one standard deviation are plotted for each month.

TABLE 2.—*Vertical vector correlations of height fields*

Wave	10-mb height vs. 500-mb height			
	Dec. 1967–Jan. 1968 (38 days)	Nov. 1964	Dec. 1964	Jan. 1965
1,2	.33	.45	.63	.41
1,4	.36	.45	.47	.42
2,3	.16	.37	.40	.80
2,5	.32	.88	.88	.89

Wave	150-mb height vs. 500-mb height		
	Dec. 1967–Jan. 1968 (29 days)	Nov. 1963	Dec. 1963
1,2	.38	.82	.78
1,4	.71	.98	.95
2,3	.33	.54	.50
2,5	.68	.80	.83

Wave	10-mb height vs. 150-mb height
	Dec. 1967–Jan. 1968 (46 days)
1,2	.60
1,4	.48
2,3	.65
2,5	.76

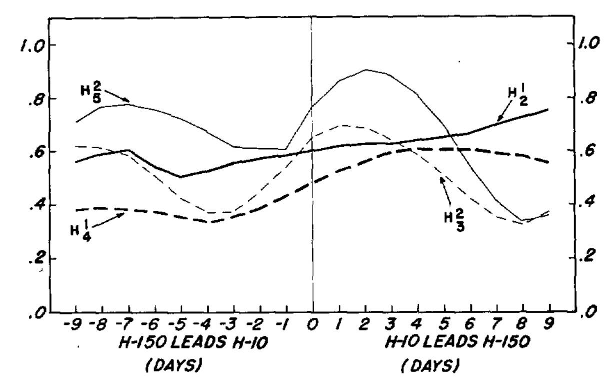

FIGURE 14.—Vector correlation coefficients of spherical harmonic waves H_2^1, H_4^1, H_3^2, and H_5^2 for 10 mb vs. 500 mb with leads and lags up to 9 days. Period of correlation is Dec. 15, 1967, through Jan. 31, 1968, with January 3 and 10 missing.

1) As during the January 1963 warming, the development of the warming was associated with a change in the height field from a circumpolar to a bipolar pattern.

2) Although anomalously high temperatures and wind speeds were observed at high stratospheric and mesospheric levels, no relationship with the middle stratospheric warming event could be demonstrated because of insufficient data.

3) A 50-mb warming followed the path of the 10-mb warming with a lag of up to 1 week. At the 50-mb level over the Canadian Arctic, temperature gradients were stronger than and in the opposite direction from those commonly observed at this season, level, and location.

4) Following the warming, thermal and circulation patterns were restored to weak winter conditions until the final warming.

5) On constant-height density charts, low- and high-density centers at 30 and 40 km were displaced from their usual positions during the warming. There was a decrease in the maximum density gradients as well as a 90° shift in the orientation of these gradients.

6) Standard deviations of analyzed daily temperature values from their monthly means for December at locations affected by the warming were two to three times those for nonwarming months of December. Temperature traces showed bimodal distributions during the warming. Following the warming, standard deviations were lower in value than during corresponding months of nonwarming winters.

7) Spherical harmonic analyses of height fields indicate closer correlations between 150 mb and 10 mb than between 150 mb and 500 mb. Highest correlation coeffi-

TABLE 3.—*Vector autocorrelations (1-day lags)*

Wave	Height of 10-mb level Dec. 1967–Jan. 1968 (38 days)	Nov. 1964	Dec. 1964	Jan. 1965
1, 2	.58	.19	.73	.23
1, 4	.63	.31	.69	.25
2, 3	.45	.51	.69	.46
2, 5	.40	.71	.71	.52
	Height of 150-mb level			
Wave	Dec. 1967–Jan. 1968	Nov. 1963	Dec. 1963	
1, 2	.61	.29	.57	
1, 4	.35	.47	.56	
2, 3	.56	.46	.41	
2, 5	.69	.55	.52	

cients were found for wave H_5^2. A vertical phase shift of 2 to 3 days between 10 and 150 mb was apparent for the broadest scales of the waves, with 10-mb waves leading the 150-mb waves. Autocorrelations for TPSW components of zonal wave number 1 at the 10-mb level were higher than those typically observed during winter months, suggesting that the TPSW at this level was relatively independent of the TPSW at other levels. Autocorrelations for wave number 2 components of the TPSW were noticeably smaller, suggesting increased vertical interactions or nonlinear interactions of these components during the warming.

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